A Novel Method for Vector Control of Three-Phase Induction Motor under Open-Phase Fault

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Abstract. The majority of electrical machines such as induction motors can be modeled by an equivalent two-phase machine model (d-q model). A three-phase induction motor with one of the stator phases opened (faulty three-phase induction motor) can be also modeled by an equivalent two-phase machine. If a conventional vector control method for balanced three-phase induction motors is used for this faulty machine, significant oscillations in speed and torque will result. In this paper, a novel technique for vector control of faulty three-phase induction motors based on rotor-field oriented control (RFOC) is presented. The performance of the proposed method was evaluated using MATLAB software. The results show that it achieves significant improvements in the oscillation reduction of the speed and torque responses.

Keywords: *field-oriented control; open-phase fault; speed and torque oscillations; three-phase induction motors; vector control.*

1 Introduction

Nowadays, field-oriented control (FOC) of induction motors (IMs) is broadly adopted to obtain high dynamic performance in drive systems. Applying a conventional control strategy such as FOC to a faulty three-phase IM (three-phase machine under open-phase fault) will result insignificant oscillations in the speed and torque output [1-4]. It was shown in [1-4] that using transformation matrices, the FOC equation structure for a faulty three-phase IM can be transformed into a structure that is similar to that for a balanced IM. However, the backward terms of the stator voltage equations were neglected in the process of calculating the FOC equations [2,3]. The proposed method in [4] for vector control of faulty IMs is also extremely dependent on the regulation of the current proportional-integral controller. Reference [5] reviews and compares fault tolerant AC drives on the basis of features, costs and limitations.

It is also interesting to note that the three-phase IM model with one phase cut-off is, in principle, similar to the model of a single-phase IM with two windings.

Received April 23rd, 2014, Revised October 7th, 2014, Accepted for publication December 9th, 2014.
 ISSN: 2337-5779, DOI: 10.5614/j.eng.technol.sci.2015.47.1.3

In other words, a single-phase IM can be considered and classified as an unbalanced two-phase IM. It is proposed in [1,6] to use a hysteresis current controller for rotor field-oriented control (RFOC) of unbalanced two-phase IMs. However, using a hysteresis current controller has drawbacks under light load conditions. In [7], stator field-oriented control (SFOC) of single-phase IMs with a positive-negative sequence current controller is proposed; the use of this controller resulted in a complex control system. In [8], decoupling vector control of single-phase IMs by introducing two decoupling signals in addition to the decoupling signals like the ones used in three-phase IM drives was proposed. Reference [9] proposes an RFOC method for symmetrical two-phase IMs as a replacement for vector control of asymmetrical two-phase IMs. This method cannot be used for vector control of faulty IMs due to the unequal inductances in the faulty IM model.

In the majority of the previously presented FOC control schemes for two-phase IMs, the supposition $(M_{qs}/M_{ds})^2=L_{qs}/L_{ds}$ is employed [5,7,8,10-13]. Using this supposition is reflected in the speed and torque responses of the faulty IM as fully discussed in[4]. It was shown in [4] that a small magnitude of oscillations at the synchronous frequency existed in the faulty IM's speed and torque responses when the supposition $L_{qs}/L_{ds}=(M_q/M_d)^2$ was used. The main contribution of the present study was to develop a novel and exact vector control method based on RFOC for IMs, which can also be adopted for IMs under open-phase fault. In the proposed method, the supposition of $(M_{qs}/M_{ds})^2=L_{qs}/L_{ds}$, which is usually considered in the FOC of two-phase IMs, is not used. The performance of the proposed method was evaluated and checked using MATLAB software.

2 Mathematical Modeling

As shown in [3], a faulty IM equation structure is, in general, the same as a balanced IM equation structure. The differences between the models of a balanced and a faulty IM are summarized in Table 1.

In this paper, v^s_{ds},v^s_{qs} are the stator d-q axis voltages, i^s_{ds},i^s_{qs} are the stator d-q axis currents, λ^s_{ds},λ^s_{qs} are the stator d-q axis fluxes, i^s_{dr}, i^s_{qr} are the rotor d-q axis currents, and λ^s_{dr}, λ^s_{qr} are the rotor d-q axis fluxes. Moreover, r_s and r_r indicate the stator and rotor resistances, L_{ds}, L_{qs}, L_r, M_{ds} and M_{qs} indicate the stator and rotor self and mutual inductances.

τ_e, τ_l, J and F are electromagnetic torque, load torque, inertia and viscous friction coefficient respectively, ω_r is the rotor speed and T_r is the rotor time constant. Moreover, the superscripts "*s*" and "*e*" indicate that the variables are in the stationary and rotating reference frame respectively.

Table 1 Comparison between models of balanced and faulty induction motor.

Balanced Induction Motor	**Faulty Induction Motor**
q-axis mutual inductance: $M_{qs} = M = \frac{3}{2} L_{ms}$	q-axis mutual inductance: $M_{qs} = \frac{\sqrt{3}}{2} L_{ms}$
q-axis self inductance: $L_{qs} = L_s = L_{ls} + \frac{3}{2} L_{ms}$	q-axis self inductance: $L_{qs} = L_{ls} + \frac{1}{2} L_{ms}$

A faulty IM stator equation can be transformed into an unbalanced d-q stator equation using the normalized transformation matrix as derived in [3], which is given by (1):

$$\left[T_s^{fault}\right] = \frac{\sqrt{2}}{2}\begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \tag{1}$$

In RFOC, the machine equations are transformed to the rotating reference frame. The transformation is performed using the well-known rotational transformation matrix given by (2) [14] (in (2), θ_e is the angle between the stationary reference frame and the rotating reference frame):

$$\left[T_s^e\right] = \begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix} \tag{2}$$

By applying (2) to the equations of the faulty three-phase IM, the stator and rotor voltage equations in the rotating reference frame can be obtained as forward and backward components [4]. The backward terms are produced because of different inductances in the faulty IM equations. It is possible to control a faulty IM by using the forward and backward components separately; however, this will result in a very complex control system. We solved this problem by introducing two rotational transformations. It will be shown that by using these rotational transformations, the RFOC equation structure of the faulty IM becomes similar to that of the balanced IM.

3 Equations of the Proposed Vector Control for Faulty IMs

The main idea of using these transformations is obtained from the simplified steady-state equivalent circuit of a single-phase IM as shown in Figure 1. All of the parameters in Figure 1 are defined in [15] and (3).

$$
\begin{aligned}
Z_F &= \frac{Z_d}{Z_{lm} + 2Z_b + Z_d}, Z_B = \frac{Z_d}{Z_{lm} + 2Z_f + Z_d} \\
Z' &= \frac{Z_{lm} + 2Z_f + Z_d - Z_F Z_d}{1 - Z_F Z_B}, V' = \frac{Z_F \left(Z_{lm} + 2Z_b + Z_d - Z_B Z_d\right)}{1 - Z_F Z_B} I_b
\end{aligned} \tag{3}
$$

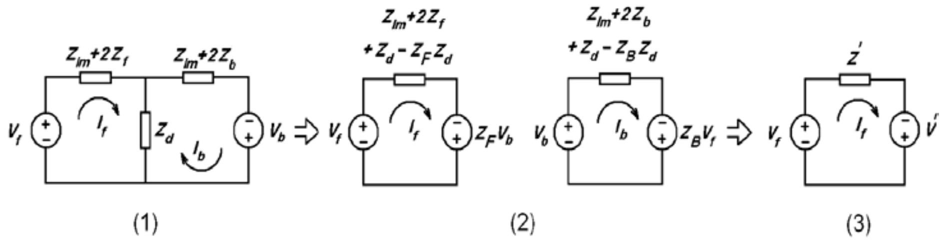

Figure 1 Equivalent circuit of a single-phase IM.

Figure 1(1) and 1(2) indicate that it is possible to change the equivalent circuit of the single-phase IM into two balanced circuits that represent the forward and backward circuits [15]. It is also possible to represent the equivalent balanced circuit (Figure 1(3)). The equations of the forward and backward voltages and currents can be represented by the following equations [15]:

$$
V_f = \frac{1}{2}\left(V_m - j\frac{V_a}{a}\right), V_b = \frac{1}{2}\left(V_m + j\frac{V_a}{a}\right), I_f = \frac{1}{2}\left(I_m - jaI_a\right), I_b = \frac{1}{2}\left(I_m + jaI_a\right) \tag{4}
$$

Eq. (4) is the transformation matrix for the transformation of the variables from unbalanced mode to balanced mode (e.g. the steady-state equivalent circuit of a single-phase IM to Figure 1(3)). Based on (4), the transformation matrices for the transformation of the variables from an unbalanced set to a balanced set are obtained as follows [3].

$$
\begin{bmatrix} v_{ds}^e \\ v_{qs}^e \end{bmatrix} = \left[T_{vs}^e\right] \begin{bmatrix} v_{ds}^s \\ v_{qs}^s \end{bmatrix} = \begin{bmatrix} \frac{M_{qs}}{M_{ds}} \cos\theta_e & \sin\theta_e \\ -\frac{M_{qs}}{M_{ds}} \sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} v_{ds}^s \\ v_{qs}^s \end{bmatrix} \tag{5}
$$

$$
\begin{bmatrix} i_{ds}^e \\ i_{qs}^e \end{bmatrix} = \left[T_{is}^e\right] \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} = \begin{bmatrix} \frac{M_{ds}}{M_{qs}} \cos\theta_e & \sin\theta_e \\ -\frac{M_{ds}}{M_{qs}} \sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} \tag{6}
$$

It is expected that by applying these rotational transformations (Eqs. (5) and (6)) to the equations of the faulty IM, the unbalanced equations of the faulty motor can be transformed into equations that have a structure similar to those of the balanced motor (see Table 2). The differences between the RFOC equations of conventional vector control for the balanced IM and the RFOC equations of the proposed modified vector control for the faulty IM using the transformation matrices are summarized in Table 2 (in RFOC: $\lambda_{dr}^{e}=|\lambda_r|$ and $\lambda_{qr}^{e}=0$). It is concluded from Table 2 that the only difference between the RFOC equations for the balanced IM and those for the faulty IM is that in faulty mode $M=M_{qs}=\sqrt{3}/2L_{ms}$, $L_s=L_{qs}=L_{ls}+1/2L_{ms}$ is obtained and we have the backward terms as defined in Table 2 ($v_{ds}^{ref\text{-}b}$, $v_{ds}^{d\text{-}b}$, $v_{qs}^{ref\text{-}b}$and $v_{qs}^{d\text{-}b}$), whereas in balanced mode, we have $M=3/2L_{ms}$, $L_s=L_{ls}+3/2L_{ms}$ and there are no backward terms. Based on Table 2, Figure 2 is proposed for fault-tolerant three-phase IM vector control.

Table 2 Comparison between two vector control methods.

Balanced IM	Faulty IM
q-axis mutual inductance: $M_{qs}=M=\frac{3}{2}L_{ms}$	q-axis mutual inductance: $M_{qs}=\frac{\sqrt{3}}{2}L_{ms}$
Stator self inductance: $L_s=L_{ls}+\frac{3}{2}L_{ms}$	Stator self inductance according to (17): $L_s=L_{qs}=L_{ls}+\frac{1}{2}L_{ms}$
2 to 3 transformation for the stator voltages: $\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix} +1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} v_{ds}^{s} \\ v_{qs}^{s} \end{bmatrix}$	2 to 2 transformation for the stator voltages: $\begin{bmatrix} v_{as} \\ v_{bs} \end{bmatrix}=\left(\frac{\sqrt{2}}{2}\begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix}\right)^{-1}\begin{bmatrix} v_{ds}^{s} \\ v_{qs}^{s} \end{bmatrix}$
3 to 2 transformation for the stator currents: $\begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix} +1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix}$	2 to 2 transformation for the stator currents: $\begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix}=\frac{\sqrt{2}}{2}\begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix}\begin{bmatrix} i_{as} \\ i_{bs} \end{bmatrix}$
Inverse of balanced rotational transformation for the stator voltages: $\begin{bmatrix} v_{ds}^{s} \\ v_{qs}^{s} \end{bmatrix}=\left(\begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix}\right)^{-1}\begin{bmatrix} v_{ds}^{e} \\ v_{qs}^{e} \end{bmatrix}$	Inverse of unbalanced rotational transformation for the stator voltages: $\begin{bmatrix} v_{ds}^{s} \\ v_{qs}^{s} \end{bmatrix}=\left(\begin{bmatrix} \frac{M_{qs}}{M_{ds}}\cos\theta_e & \sin\theta_e \\ -\frac{M_{qs}}{M_{ds}}\sin\theta_e & \cos\theta_e \end{bmatrix}\right)^{-1}\begin{bmatrix} v_{ds}^{e} \\ v_{qs}^{e} \end{bmatrix}$

Balanced IM	Faulty IM
Balanced rotational transformation for the stator currents: $\begin{bmatrix} i_{ds}^{e} \\ i_{qs}^{e} \end{bmatrix} = \begin{bmatrix} \cos\theta_e & \sin\theta_e \\ -\sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix}$	Unbalanced rotational transformation for the stator currents: $\begin{bmatrix} i_{ds}^{e} \\ i_{qs}^{e} \end{bmatrix} = \begin{bmatrix} \frac{M_{ds}}{M_{qs}}\cos\theta_e & \sin\theta_e \\ -\frac{M_{ds}}{M_{qs}}\sin\theta_e & \cos\theta_e \end{bmatrix} \begin{bmatrix} i_{ds}^{s} \\ i_{qs}^{s} \end{bmatrix}$
Stator d-axis voltage: $v_{ds}^{e} = r_s i_{ds}^{e} + \hat{L}_s \frac{d}{dt} i_{ds}^{e} - \omega_e \hat{L}_s i_{qs}^{e}$ $+ \frac{M^2}{L_r} \frac{d}{dt} (\frac{\lvert\lambda_r\rvert}{M})$ where: $\hat{L}_S = L_S - \frac{M^2}{L_r}$	Stator d-axis voltage: $v_{ds}^{e} = r_s i_{ds}^{e} + L_s' \frac{d}{dt} i_{ds}^{e} - \omega_e L_s' i_{qs}^{e}$ $+ \frac{M_{qs}^2}{L_r} \frac{d}{dt} (\frac{\lvert\lambda_r\rvert}{M_{qs}}) + v_{ds}^{d-b} + v_{ds}^{ref-b}$ where: $L_s' = L_{qs} - \frac{M_{qs}^2}{L_r}, v_{ds}^{d-b} = -\omega_e (\frac{M_{qs}^2}{M_{ds}^2} L_{ds} - L_{qs}) i_{qs}^{-e}$ $v_{ds}^{ref-b} = \left((\frac{M_{qs}^2}{M_{ds}^2} r_s - r_s) i_{ds}^{-e} + (\frac{M_{qs}^2}{M_{ds}^2} L_{ds} - L_{qs}) \frac{di_{ds}^{-e}}{dt} \right)$ $\begin{bmatrix} i_{ds}^{-e} \\ i_{qs}^{-e} \end{bmatrix} = \begin{bmatrix} \cos^2\theta_e & -\sin\theta_e \cos\theta_e \\ -\sin\theta_e \cos\theta_e & \sin^2\theta_e \end{bmatrix} \begin{bmatrix} i_{ds}^{e} \\ i_{qs}^{e} \end{bmatrix}$
Stator q-axis voltage: $v_{qs}^{e} = r_s i_{qs}^{e} + \hat{L}_s \frac{d}{dt} i_{qs}^{e} + \omega_e \hat{L}_s i_{ds}^{e}$ $+ \omega_e \frac{M}{L_r} \lvert\lambda_r\rvert$	Stator q-axis voltage: $v_{qs}^{e} = r_s i_{qs}^{e} + L_s' \frac{d}{dt} i_{qs}^{e} + \omega_e L_s' i_{ds}^{e}$ $+ \omega_e \frac{M_{qs}}{L_r} \lvert\lambda_r\rvert + v_{qs}^{d-b} + v_{qs}^{ref-b}$ where: $v_{qs}^{d-b} = \omega_e (\frac{M_{qs}^2}{M_{ds}^2} L_{ds} - L_{qs}) i_{ds}^{-e}$ $v_{qs}^{ref-b} = \left((\frac{M_{qs}^2}{M_{ds}^2} r_s - r_s) i_{qs}^{-e} + (\frac{M_{qs}^2}{M_{ds}^2} L_{ds} - L_{qs}) \frac{di_{qs}^{-e}}{dt} \right)$

4 Simulation Results and Comparisons

To show the effectiveness of the proposed drive system, a simulation of the system was conducted using MATLAB software. The simulated motor was fed by a pulse width modulation (PWM) three-leg voltage source inverter (VSI). The Runge-Kutta algorithm was used for solving the faulty three-phase IM dynamic equations. The simulated three-phase IM data were as follows: voltage:125V, f=50Hz, number of poles=4, power=475W, r_s=20.6Ω, r_r=19.15Ω, L_{lr}=L_{ls}=0.0814H, L_m=0.851H, J=0.0038kg.m^2. The reference speed in the simulation was set to 400rpm and the load torque was varied as follows: from

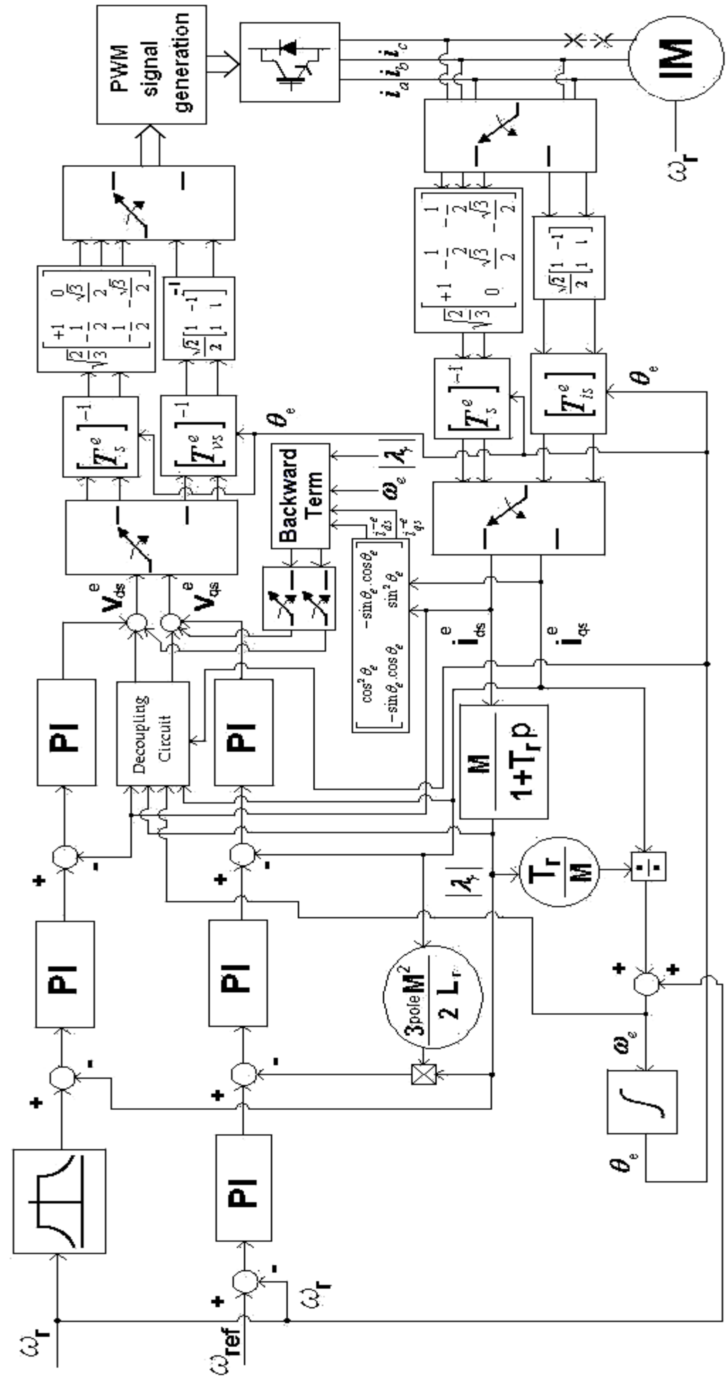

Figure 2 Block diagram of the proposed vector control for fault-tolerant IM.

t=0s to t=0.4s, T_l=0N.m, from t=0.4s to t=3s, T_l=1N.m and from t=3s to t=7s, T_l=1.5N.m. The RFOC using the conventional and the proposed modified controller based on Figure 2 were simulated with the fault introduced at t=1s.

Figure 3 demonstrates that the conventional vector controller cannot control the faulty IM properly. Especially we see a considerable oscillation in the electromagnetic torque and motor speed (as can be seen from Figure 3, when using the conventional controller, the speed oscillation after applying load and at steady state is ~12 rpm at a rotor speed of 400rpm, whereas when using the modified controller, the speed oscillation was reduced notably to ~0.8rpm). The results show that the modified RFO controller decreased the torque oscillations significantly with an improvement in the motor speed response.

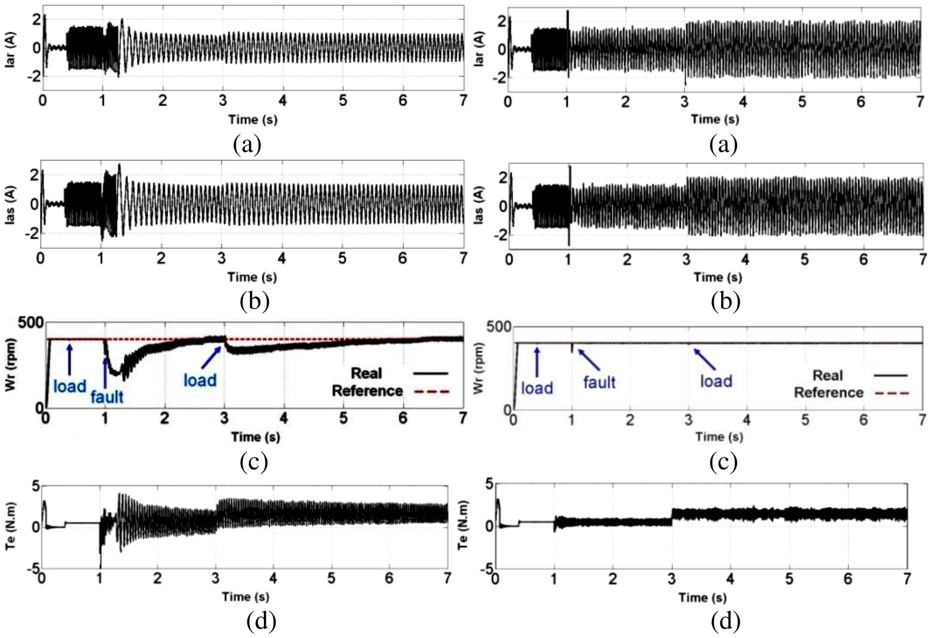

Figure 3 Simulation results of the conventional (left) and modified (right) controller: (a) rotor a-axis current, (b) stator a-axis current, (c) speed, (d) torque.

5 Conclusion

In this paper, a novel approach of vector control for faulty three-phase or unbalanced two-phase IMs, based on RFOC is proposed. The technique employs two new transformation matrices that transform the RFOC equations of an unbalanced two-phase IM into equations that have the same structure as those of a balanced three-phase IM. This scheme not only can be used for the vector control of unbalanced IMs but also is appropriate for single-phase IMs.

Unlike other RFOC implemented for single-phase or unbalanced IMs, the technique proposed in this paper does not employ the supposition $(M_{qs}/M_{ds})^2=L_{qs}/L_{ds}$. The results indicate that the proposed technique can considerably reduce speed and torque oscillations.

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